



# Phytoplankton response to climate changes and anthropogenic activities recorded by sedimentary pigments in a shallow eutrophied lake

Hanxiao Zhang<sup>a</sup>, Shouliang Huo<sup>a,\*</sup>, Kevin M. Yeager<sup>b</sup>, Zhuoshi He<sup>a</sup>, Beidou Xi<sup>a</sup>, Xiaochuang Li<sup>a</sup>, Chunzi Ma<sup>a</sup>, Fengchang Wu<sup>a</sup>

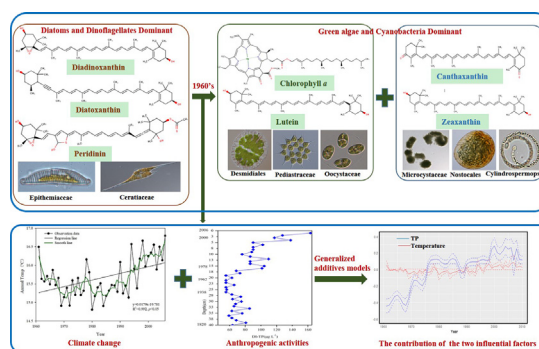
<sup>a</sup> State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Science, Beijing 100012, China

<sup>b</sup> Department Earth and Environmental Sciences, University of Kentucky, Lexington, KY 40506, United States of America

## HIGHLIGHTS

- Phytoplankton community structures can be reconstructed by sedimentary pigments.
- Phytoplankton succession has been driven by climate change and human activities.
- GAMs were applied to quantify the effects of climate change and human activities.
- The adaptation of lake management policies to climate change should be considered.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

### Article history:

Received 27 June 2018

Received in revised form 4 August 2018

Accepted 5 August 2018

Available online 7 August 2018

Editor: Ouyang Wei

### Keywords:

Algae succession

Anthropogenic activities

Climate change

Generalized additive models

Phytoplankton pigments

## ABSTRACT

Studies that address the potential effects of climate and anthropogenic activities on lacustrine phytoplankton succession are scarce in the shallow lakes. In the present work, the succession of phytoplankton community inferred from sedimentary pigments has been investigated; the impacts of climate and anthropogenic activities on the succession have been evaluated by the generalized additive models (GAMs) in a shallow eutrophied lake, Lake Chaohu, located eastern China. The results show that phytoplankton succession can be divided into two periods: pre-1960s and post 1960s. The mean values of  $\beta\beta$  Car and Chl *a* increased after the 1960s at both sites sampled, from 0.013 to 0.359, and 0.013 to 1.382  $\mu\text{g g}^{-1}$ , respectively (site C4), and from 0.015 to 0.530, and 0.010 to 0.921  $\mu\text{g g}^{-1}$ , respectively (site C14), reflecting significant increases of primary productivity since the 1960s. The percentage of diatoms and dinoflagellates preserved in sediments decreased from ~90% to ~15% since the 1960s, while cyanobacteria and green algae increased from ~5% to ~35%, respectively, reflecting the shift of the lake phytoplankton community. This succession was related to construction of the Chaohu Dam in 1963, increasing discharges of anthropogenic N and P into the Lake, and a generally warming environment as reflected by increasing average air temperatures. The results of GAMs showed aquatic total phosphorus (TP) concentration is the dominant contributor to phytoplankton community change, explaining 42.74%, 40.27%, 40.77% and 72.28% of the variance of total algae, cyanobacteria, green algae, and diatoms and dinoflagellates, respectively. The positive impacts of increasing TP concentrations on abundances of total algae, cyanobacteria, and green algae were observed during periods of relatively high TP concentrations since the mid-1970s. The positive responses of total algae, cyanobacteria, green algae and diatoms and dinoflagellates to increasing average air temperatures were observed since the mid-1990s, showing that a generally warmer environment facilitated algae proliferation.

© 2018 Elsevier B.V. All rights reserved.

\* Corresponding author.

E-mail address: [huosl@craes.org.cn](mailto:huosl@craes.org.cn) (S. Huo).

## 1. Introduction

Anthropogenic activities and climate change can both alter strongly lacustrine primary production and phytoplankton community structures over decadal to centennial time scales (Michalak, 2016; Hayes et al., 2016; Zhen et al., 2016; O'Beirne et al., 2017). Tracking the succession of phytoplankton communities over decadal time scales is important to better understand how lakes have responded historically to climate change and human activities, as well as in formulating sound ecosystem management strategies (Hayes et al., 2016; Jambirina-Enríquez et al., 2017; O'Beirne et al., 2017). Due to the absence of historical ecological and water quality data in most of lakes, biomarkers (lipids, DNA, phytoplankton pigments, etc.) preserved in lake sediment cores have been used to track the changes of various phytoplankton communities over time (Afrifa et al., 2016; Capo et al., 2017; Deshpande et al., 2014; Chen et al., 2015; Szymczak-Żyła et al., 2016). Fossil phytoplankton pigments have become one of the most popular tools to estimate algae biomass and phytoplankton successions (Reuss et al., 2005; Deshpande et al., 2014; Chen et al., 2015; Szymczak-Żyła et al., 2016). Individual carotenoids have often been used to learn about the histories of specific members of algae communities, including alloxanthin (cryptophytes), canthaxanthin and zeaxanthin (cyanobacteria), diatoxanthin and diadinoxanthin (diatoms and dinoflagellates), and lutein (green algae and higher plants), while chlorophyll-*a* and  $\beta\beta$  carotene have been used as proxies for total algal biomass (Reuss et al., 2005; Deshpande et al., 2014; Szymczak-Żyła et al., 2016).

The preservation of pigments in sediment may change over time in association with changes in primary production, and *syn*- and post-depositional conditions, and as a function of pigment chemical stability (Reuss et al., 2005; Szymczak-Żyła et al., 2011, 2016). Pigment degradation in the water column and sediments is influenced by photo- and chemical oxidation rates (which vary with temperature, light, and oxygen), herbivore grazing, as well as bacterial degradation rates (Chen et al., 2015; Szymczak-Żyła et al., 2016). Therefore, the ability of pigment profile concentration data preserved in sediments to reconstruct historical primary productivity is determined by the impacts of diagenetic conditions on the fossil pigments. Pheophytins, dominant and stable chlorophyll-*a* degradation product, can be used to evaluate the preservation conditions of pigments (Waters et al., 2005; Chen et al., 2015). Previous research conducted in four estuaries located in Northern Europe found that permanent anoxic environments with limited resuspension and no bioturbation are ideal preservation conditions for pigments in sediment (Reuss et al., 2005). And these conditions can be indicated by low pheopigment-*a*/chlorophyll-*a* ratio values, or high total carotenoid/total identified pigments ratio values (Reuss et al., 2005).

Recent studies have focused on the use of preserved phytoplankton pigments to track changes in algae community structure and biomass caused by eutrophication, acidification, ultraviolet radiation, and grazing intensity in sediments of marine, coastal and estuarine settings (Reuss et al., 2005; Szymczak-Żyła et al., 2011; Chen et al., 2015; Szymczak-Żyła et al., 2016; Jiang et al., 2017). In contrast to open marine settings and deep lakes, pigments found in sediments of shallow lakes tend to be well-preserved because of the relatively short time scales of settling and deposition, with less risk of being grazed by zooplankton and fish (Scheffer, 2004; Deshpande et al., 2014; Zastepa et al., 2017). Despite the preservation potential of pigments in the sediments of shallow lakes, relatively little is known about long-term phytoplankton community changes in these aquatic settings (Waters et al., 2005; Romero-Viana et al., 2010). Furthermore, cyanobacteria blooms caused by human activities and climate change have been identified as a serious problem for shallow lakes in recent decades (Michalak, 2016; Shi et al., 2017). It is therefore essential to quantify the contributions of climate change and human activities to changes in phytoplankton community composition and overall abundance. The complex linkages between human activities, climate change, and hydrological processes in these small basins can be particularly challenging to unravel in shallow lakes (Mwangi et al., 2016; Afrifa et al., 2016; Toride et al., 2018).

This research is aimed at reconstructing phytoplankton abundances and community structures over the past one hundred years in the shallow and eutrophic Lake Chaohu in eastern China, by the extraction and analysis of fossil pigments from two dated sediment cores. We hypothesized that this lake has experienced a major change in phytoplankton community structure over the past one hundred years. And the succession of phytoplankton community has been driven by climate change and human activities, particularly over the last six decades, a period of rapid economic development in this region. The specific objectives of this study were to: (1) analyze the concentration profile of phytoplankton pigments in lake sediments to reconstruct changes in the phytoplankton community structure over the last 100 years; and (2) quantify the influence of the climate change and anthropogenic activities on phytoplankton succession using generalized additive models (GAMs).

## 2. Materials and methods

### 2.1. Study area and sampling

Lake Chaohu is the fifth largest freshwater lake in China (Fig. 1, 31°25'–31°43'N, 117°16'–117°51'E) and is shallow and severely eutrophied. It is located in the lower reach of the Yangtze River, with a surface area of 780 km<sup>2</sup>, a catchment area of 12,938 km<sup>2</sup>, and a mean

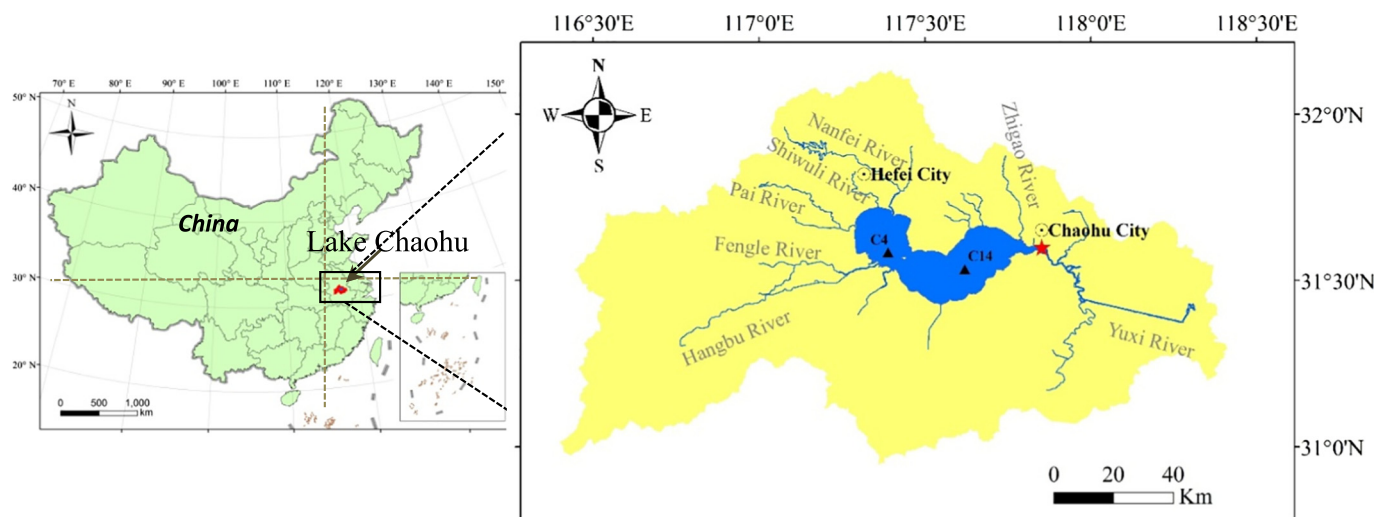
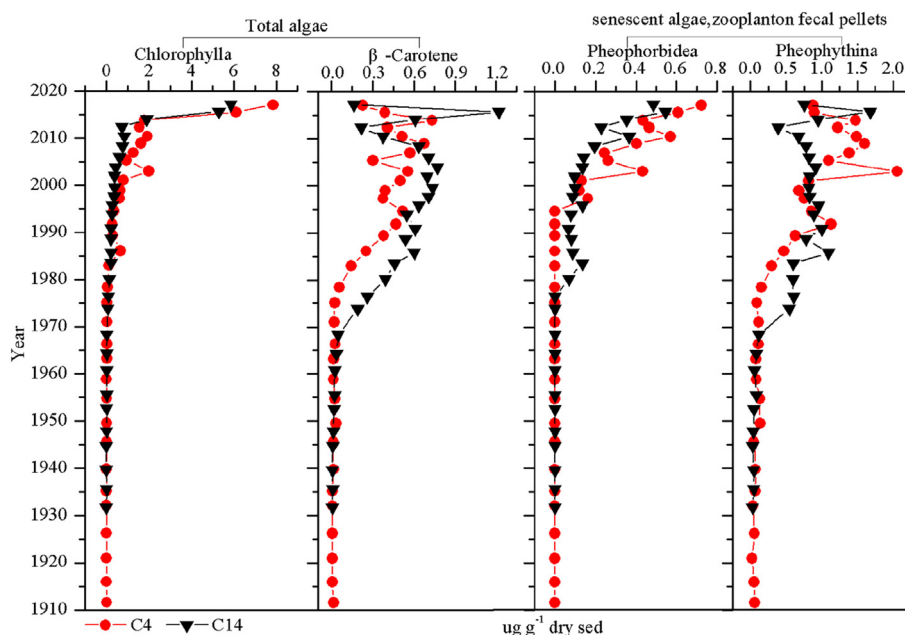


Fig. 1. Location of the sampling sites in Lake Chaohu, China.

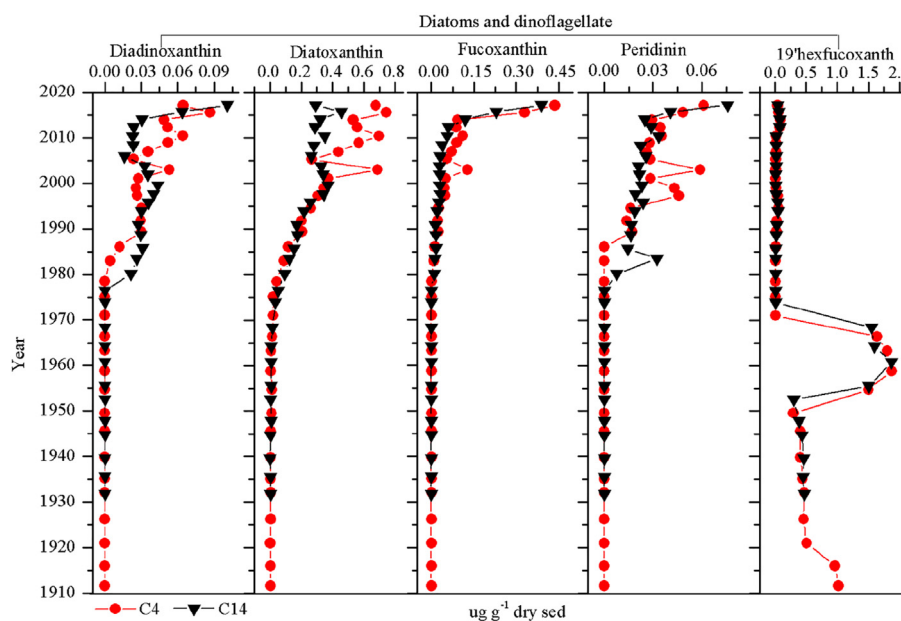
depth of ~3.0 m (Huo et al., 2017). The Yuxi River, the lake's only outflow, served as a channel for the exchange of water between the lake and the Yangtze River before construction of the Chaohu Dam on the Yuxi River was completed in 1963 (Fig. 1). The hydrodynamic conditions of Lake Chaohu have changed markedly since then, as the amount of annual water exchange between the lake and the Yangtze River was reduced from  $13.6 \times 10^8$  to  $1.6 \times 10^8$  m<sup>3</sup> after its impoundment (Li et al., 2015; Huo et al., 2017). Both water quality and the aquatic ecology of the lake have changed significantly after construction of Chaohu Dam, and in response to the increasing pressures of population growth, heavy urbanization, agriculture and industrial production, and tourism (Huo et al., 2017). The lake has suffered serious eutrophication due to

increasing inputs of nutrients from agricultural and industrial sources during recent decades (Zan et al., 2011; Li et al., 2015). The structure of aquatic populations of animals and plants in Lake Chaohu has changed (i.e., decreasing numbers of large fish, herbivorous fish, and macrophytes) due to the impacts of climate change, hydrological processes and human activities, such as development of industrial and urban areas, utilization of fertilizers (Chen et al., 2011; Zhang et al., 2012; Zhang et al., 2014).

The sampling sites were selected away from lake banks, the lake outlet, and inflowing streams to avoid locations where sediment disturbance by mixing and re-suspension would be likely (Li et al., 2015; Huo et al., 2017). Two cores (C4, C14) were collected from the central

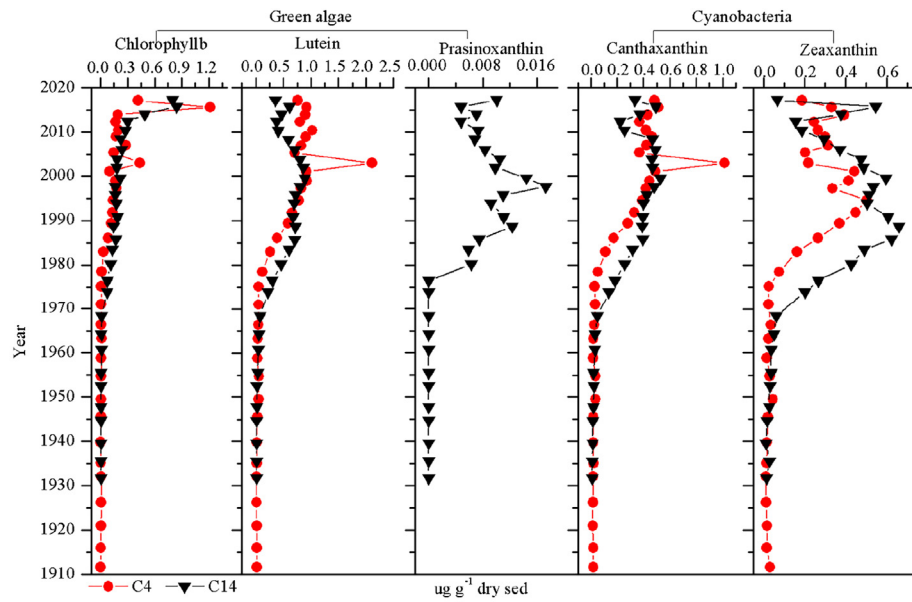


(a)

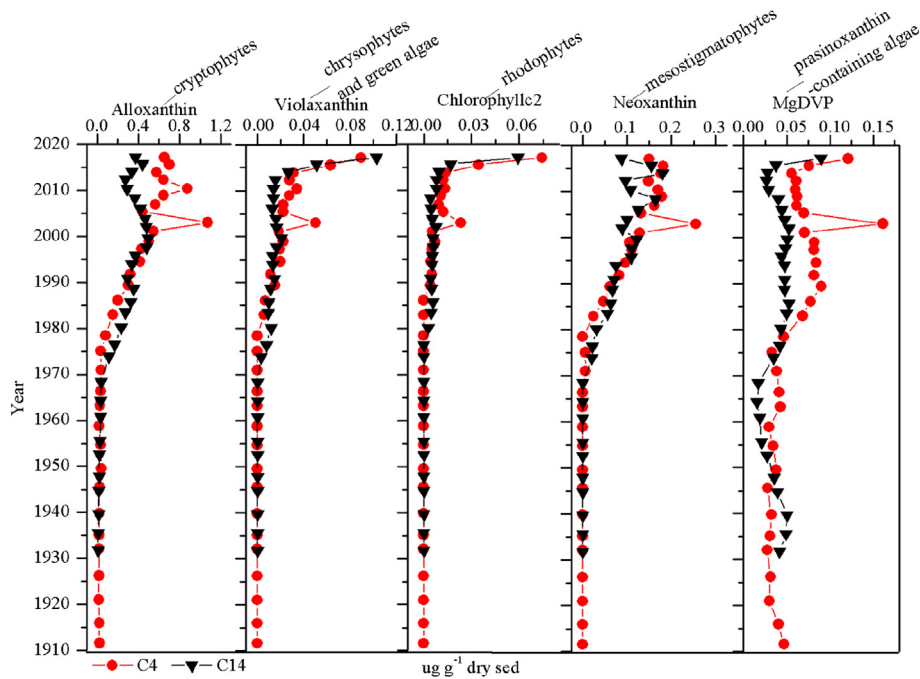


(b)

Fig. 2. Concentration profiles of photosynthetic pigments in sediments of cores C4 and C14.



(c)



(d)

Fig. 2 (continued).

areas of the western and eastern sections of the lake, respectively. Sediment cores were collected in December 2017 using a gravity corer outfitted with a PMMA acrylic tube (inner diameter of 8 cm, length of 50 cm). These cores were sub-sectioned at 1-cm intervals between 0 and ca. 30 cm. Cores C4 and C14 were divided into 33 and 30 sub-samples, respectively.

The sub-samples were stored in a cold box and transported to the laboratory out of the sunlight to reduce the photodegradation of fossil pigments. Interval samples were weighed and freeze-dried, homogenized, sieved through a 100-mesh sieve, and stored at  $-80^{\circ}\text{C}$ , prior to extraction and analysis of pigments.

## 2.2. Sample extraction and analysis

For each sample, approximately 1 g of dried sediment was placed in a 10 ml polyethylene plastic centrifuge tube and extracted with 3 ml of an acetone-water mixture (95:5 v:v). Extraction continued while sample tubes were in an ice-water bath, followed by a 15 minute ultrasonic treatment, and then samples were stored in the freezer ( $-80^{\circ}\text{C}$ ) for 24 h in the dark. Sample extracts were purified by filtration through a  $0.22\text{ }\mu\text{m}$  PTFE filter, and stored. Sample extracts were kept in the dark and stored at  $-80^{\circ}\text{C}$  until analysis by high performance liquid chromatography (HPLC) (Jiang et al., 2017).

**Table 1**

Pearson correlation matrix for nutrients proxies, particle size and phytoplankton pigments from cores C4 and C14.

	TN	TP	TOC	$\delta^{15}\text{N}$	$\delta^{13}\text{C}$	d < 4 $\mu\text{m}$	4–8 $\mu\text{m}$	8–16 $\mu\text{m}$	16–64 $\mu\text{m}$	HexFuco	Allo	Cantha
TN	1											
TP	0.963**	1										
TOC	0.896**	0.831**	1									
$\delta^{15}\text{N}$	0.977**	0.967**	0.888**	1								
$\delta^{13}\text{C}$	−0.969**	−0.963**	−0.875**	−0.970**	1							
d < 4 $\mu\text{m}$	0.853**	0.889**	0.767**	0.886**	−0.832**	1						
4–8 $\mu\text{m}$	0.835**	0.872**	0.779**	0.874**	−0.812**	0.981**	1					
8–16 $\mu\text{m}$	−0.660**	−0.685**	−0.509**	−0.679**	0.644**	−0.741**	−0.621**	1				
16–64 $\mu\text{m}$	−0.833**	−0.871**	−0.764**	−0.870**	0.810**	−0.987**	−0.998**	0.633**	1			
HexFuco	−0.515**	−0.537**	−0.463**	−0.476**	0.511**	−0.690**	−0.678**	0.497**	0.687**	1		
Allo	0.952**	0.911**	0.778**	0.919**	−0.923**	0.775**	0.746**	−0.666**	−0.749**	−0.500**	1	
Cantha	0.941**	0.890**	0.781**	0.907**	−0.911**	0.753**	0.728**	−0.636**	−0.729**	−0.500**	0.969**	1
Chla	0.875**	0.861**	0.627**	0.833**	−0.846**	0.714**	0.667**	−0.670**	−0.678**	−0.301**	0.682**	0.618**
Chlb	0.927**	0.890**	0.738**	0.887**	−0.903**	0.739**	0.705**	−0.632**	−0.710**	−0.333**	0.716**	0.698**
Diadino	0.962**	0.918**	0.818**	0.924**	−0.951**	0.769**	0.754**	−0.592**	−0.753**	−0.466**	0.943**	0.881**
Diato	0.961**	0.916**	0.790**	0.923**	−0.930**	0.780**	0.748**	−0.676**	−0.752**	−0.473**	0.977**	0.915**
Fuco	0.901**	0.857**	0.684**	0.855**	−0.862**	0.701**	0.653**	−0.662**	−0.663**	−0.310**	0.707**	0.649**
Lut	0.939**	0.892**	0.781**	0.908**	−0.910**	0.763**	0.740**	−0.633**	−0.741**	−0.505**	0.972**	0.995**
Peri	0.913**	0.824**	0.830**	0.870**	−0.872**	0.687**	0.653**	−0.614**	−0.656**	−0.444**	0.939**	0.933**
Pheidea	0.765**	0.728**	0.513**	0.717**	−0.717**	0.568**	0.496**	−0.647**	−0.513**	−0.345**	0.855**	0.750**
Phea	0.941**	0.919**	0.726**	0.911**	−0.928**	0.764**	0.737**	−0.635**	−0.741**	−0.492**	0.966**	0.947**
Viola	0.937**	0.894**	0.771**	0.901**	−0.909**	0.745**	0.715**	−0.633**	−0.718**	−0.414**	0.870**	0.834**
Zea	0.902**	0.865**	0.902**	0.891**	−0.914**	0.784**	0.809**	−0.503**	−0.794**	−0.537**	0.783**	0.815**
$\beta$ Car	0.974**	0.938**	0.862**	0.945**	−0.971**	0.811**	0.806**	−0.607**	−0.801**	−0.529**	0.917**	0.912**

\*\* Correlations are significant at  $P < 0.01$  (two-tailed).

Pigment extract analysis was performed using an Agilent 1200 series HPLC equipped with an auto-sampler (Model G1315C) and a diode-array detector (Agilent Technologies Inc., Palo Alto, CA, USA). Pigment separation was achieved using a Waters Symmetry C8 column ( $150 \times 4.6$  mm,  $3.5 \mu\text{m}$ ) heated at  $25^\circ\text{C}$ . The flow rate was  $1.0 \text{ ml min}^{-1}$ , and the sample injection volume was  $100 \mu\text{l}$  (Jiang et al., 2017). The mobile phase consisted of three eluents: (A) acetonitrile, (B) methanol, and (C) a tetrabutylamine-acetic acid-methanol mixture. Pigment separation was analyzed using a reverse-phase protocol in accordance with methods described by Zapata (2000). The following 19 pigment standards were utilized (all from DHI Inc., Hørsholm, Denmark): chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), chlorophyll *c2* (Chl *c2*), pheophytin *a* (Phe *a*), pheoporphide *a*, (Pheide *a*), Mg 2,4 divinylpheophorbide (MgDVP), alloxanthin (Allo), canthaxanthin (Cantha),  $\beta$ ,  $\beta$  carotene ( $\beta\beta$  Car), diadinoxanthin (Diadino), diatoxanthin (Diat), fucoxanthin (Fuco), 19' hexfucoxanthin (Hex-Fuco), lutein (Lut), neoxanthin (Neo), peridinin (Peri), prasinoxanthin (Pras), violaxanthin (Viola), and zeaxanthin (Zea). Pigments were identified by comparing the retention times and signature peaks from diode-array spectroscopy results with these standards. The wavelength range of diode-array spectroscopy is 350–750 nm, and spectral resolution is 1.2 nm. All pigments were quantified at 440 nm, except for Phe *a* and Pheide *a*, which were quantified at 430 nm. All pigments concentration were calculated considering the average extinction coefficient of each pigments and the mass of the dry sediment sample, and the result expressed as micrograms per gram of dry sediment ( $\mu\text{g g}^{-1}$  dry sediment).

Total organic carbon (TOC) was determined using a TOC analyzer (multi N/C 2100, Analytik Jena AG, Jena, Germany) after the samples were pretreated with  $1 \text{ mol L}^{-1}$  HCl to remove inorganic carbon. Total nitrogen (TN) was measured using a Vario El elemental analyzer (Elementar Corporation, Hanau, Germany). Total phosphorus (TP) was extracted by  $1 \text{ mol L}^{-1}$  HCl after  $500^\circ\text{C}$  ignition (2 h). The extraction solution of TP was determined by molybdate antimony ascorbic spectrophotometer. Stable isotopes of carbon ( $\delta^{13}\text{C}_{\text{org}}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) were measured using an isotope-ratio mass spectrometer (Finnigan Delta Plusplus XP) having a precision of  $<0.1\%$  for  $\delta^{13}\text{C}$ , and  $<0.2\%$  for  $\delta^{15}\text{N}$  (Zan et al., 2012). The samples were treated with  $1 \text{ M}$  HCl to remove inorganic carbon before  $\delta^{13}\text{C}$  analysis. The sediment grain size

distribution of the samples was determined using a Malvern Mastersizer S2000 particle size analyzer (Malvern Instruments Limited, Malvern, UK; measuring range:  $0.02\text{--}2000 \mu\text{m}$ ) (Qi et al., 2015).

### 2.3. Data sources

According to Zan et al. (2011), the average sediment accumulation rates at core stations C4 and C14 were  $0.224$  and  $0.242 \text{ g cm}^{-2} \text{ y}^{-1}$ , respectively. Meteorological data for this region was extracted from the CN05.1 data set, which was constructed using the “anomaly approach” during the interpolation but with more station observation ( $\sim 2400$ ) in China. In the “anomaly approach”, a gridded climatology is first calculated, and then a gridded daily anomaly is added to the climatology to obtain the final data set (Xu et al., 2009).

TP concentrations in water are from Chen et al. (2011), who used sedimentary fossil diatom assemblages to establish a diatom-inferred total phosphorus (DI-TP) transfer function.

### 2.4. Generalized additive model

Generalized additive models (GAMs) are non-parametric extensions of generalized linear regression models, and were found to be effective here in addressing the nonlinear relationship between response variables and explanatory variables, and in obtaining better prediction results (Pearce et al., 2011; Capo et al., 2017). The general expression is:

$$g(\mu) = \beta_0 + \sum_{i=1}^k s_i(x_i) + \varepsilon \quad (2.1)$$

where  $\mu$  is the response variable,  $\beta_0$  is a constant intercept term,  $s_i(x_i)$  is the smoothing function of explanatory variable  $x_i$ , and  $\varepsilon$  is the residual with variance( $\varepsilon$ ) =  $\sigma^2$ .

GAMs were utilized to investigate relationships between phytoplankton succession and two influential factors (annual average air temperature, and aquatic TP concentration). Annual average air temperature was considered to be the main index of climate change in the Lake Chaohu basin, because the correlation between temperature and

Chla	Chlb	Diadino	Diato	Fuco	Lut	Peri	Pheidea	Phea	Viola	Zea	$\beta$ Car
1											
0.752**	1										
0.800**	0.831**	1									
0.792**	0.780**	0.980**	1								
0.997**	0.751**	0.813**	0.809**	1							
0.570**	0.673**	0.874**	0.910**	0.600**	1						
0.771**	0.722**	0.904**	0.939**	0.802**	0.914**	1					
0.886**	0.726**	0.898**	0.930**	0.894**	0.733**	0.865**	1				
0.571**	0.644**	0.901**	0.924**	0.595**	0.956**	0.864**	0.778**	1			
0.941**	0.760**	0.911**	0.921**	0.955**	0.800**	0.924**	0.923**	0.785**	1		
0.400**	0.556**	0.769**	0.733**	0.422**	0.821**	0.717**	0.463**	0.804**	0.614**	1	
0.495**	0.622**	0.879**	0.877**	0.517**	0.922**	0.816**	0.664**	0.950**	0.717**	0.932**	1

pigments concentration was more significant than that of precipitation (Fig. 6; Table 2). Moreover, previous studies indicated that rising temperature as one of the key driver of climate change enhanced algae growth rates and extended the growing season (Capo et al., 2017; Zastepa et al., 2017). TP concentrations in Lake Chaohu waters increased in the 1970s due to major contributions from anthropogenic sources (industrial and agricultural) (Zan et al., 2011). In this work, the predictor variables were TP concentrations and annual average air temperatures, while the response variables were fossil pigment concentrations. The GAM modeling function from the 'mgcv' package (Wood, 2015) in R statistical software was used to realize GAMs analysis. F tests were used to evaluate the significance of the predictive variables. Correlations with  $p < 0.01$  were regarded as significant for all GAM analysis.

## 2.5. Data processing

The relationships between pigment concentrations, nutrient concentrations (TN, TP, TOC and C/N), sediment grain size, climate factors (annual air temperature and precipitation), and  $\delta^{13}\text{C}_{\text{org}}$  and  $\delta^{15}\text{N}$  values, were analyzed by Spearman correlation analysis using SPSS18.0. Correlations where  $p < 0.05$  were considered to be significant. The cluster analysis of stratigraphic profiles of pigments concentrations was performed with the software TILIA 2.0.41, which used constrained incremental sum of squares (CONISS) with Edwards & Cavalli-Sforza's chord distance. The results of pigments distribution were plotted by OriginPro 8.0.

## 3. Results and discussion

### 3.1. Preservation conditions and pigment profiles

The pigment content in sediments depends not only on primary production but also on preservation conditions (Szymczak-Żyła et al., 2011; Szymczak-Żyła et al., 2016). Phe *a* and Pheide *a* were used to assess the degree of pigment preservation in this study, as they are the primary and most stable degradation products of Chl *a* under anoxic-hypoxic, and aerobic conditions, respectively (e.g., Reuss et al., 2005; Chen et al., 2015). Pheide *a* concentrations were not high enough to be detected in core sediments deeper than 13 cm, and 19 cm, at stations

C4 and C14, respectively. In the upper, shallower sediments, Pheide *a* concentrations were  $<0.8 \mu\text{g g}^{-1}$  dry weight (Fig. 2a), reflecting anoxic-hypoxic conditions prevailing at stations C4 and C14. The strong correlation between Pheide *a* and Chl *a* in the two cores ( $r = 0.886$ ,  $n = 63$ ,  $p < 0.01$ ; Table 1) suggests that the effect of aerobic diagenetic process on Chl *a* may be weak, since only a small fraction of Chl *a* would degrade to Pheide *a* in a dominantly anoxic environment (Chen et al., 2015). Furthermore, good pigment preservation conditions were also suggested by lower ratio values of pheopigment-*a* (sum of Phe *a* and Pheide *a*) to Chl *a* (pheopigment-*a*/Chl *a*  $< 10$ ; Fig. 3) in the two cores due to the dominantly anoxic environment (Reuss et al., 2005; Deshpande et al., 2014).

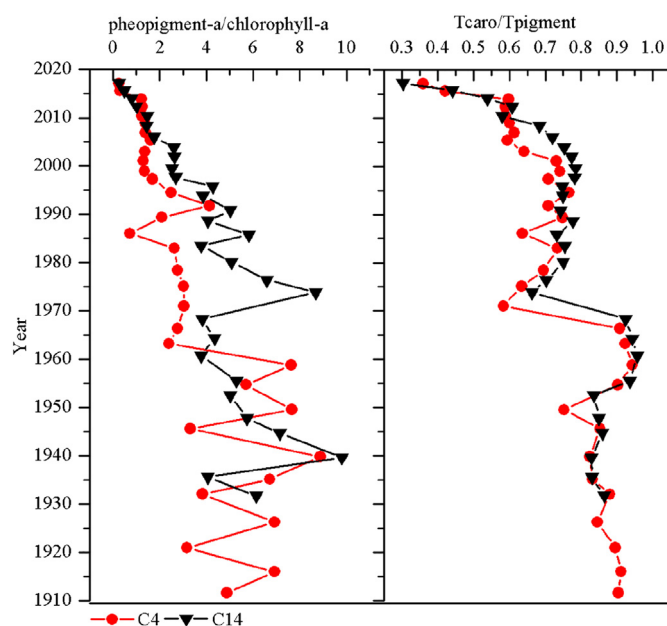


Fig. 3. Indicators of pigments degradation regime in the sediments at C4 and C14 sites.

The preservation of labile carotenoids was reflected in the high ratio values of total carotenoid (Tcaro) to total identified pigments (Tpigment), with mean values of 0.729 and 0.747, at stations C4 and C14, respectively (Fig. 3) (Reuss et al., 2005). The values of this ratio decreased from 0.91 to 0.55, and from 0.92 to 0.66, at stations C4 and C14 respectively, during the 1960s (Fig. 3). These changes may be related in part to construction of Chaohu Dam, which produced generally more stable and spatially extensive depositional conditions, and contributed to conditions more favorable to producing and maintaining an anaerobic environment, favoring pigment preservation (Chen et al., 2001; Reuss et al., 2005). We interpret these results to support limited pigment degradation overall, so that the preserved pigments accurately reflect historical environmental changes over the period of record.

Eighteen of the nineteen pigments were detected in sediment from both stations C4 and C14, with Pras only detected at station C14 (Fig. 2). Pigment concentrations in the deepest sediments sampled in these cores (except for Hex-Fuco) were minimal, and often increased toward the surface (Fig. 2; Fig. S1). The variation stages of pigment concentration profile were identified by CONISS cluster analysis. These results displayed two identifiable periods at the two stations: pre- and post-1960s (Fig. 4). Generally, the concentrations of pigments were extremely low before the 1960s (Fig. 2), indicating low phytoplankton productivity during that time even if the relatively unfavorable pigments preservation conditions were considered. The mean values of  $\beta\beta$  Car and Chl *a* in sediments from these two time periods increased from 0.013 to 0.359, and 0.013 to 1.382  $\mu\text{g g}^{-1}$  at station C4, and from 0.015 to 0.530, and 0.010 to 0.921  $\mu\text{g g}^{-1}$  at station C14 respectively.

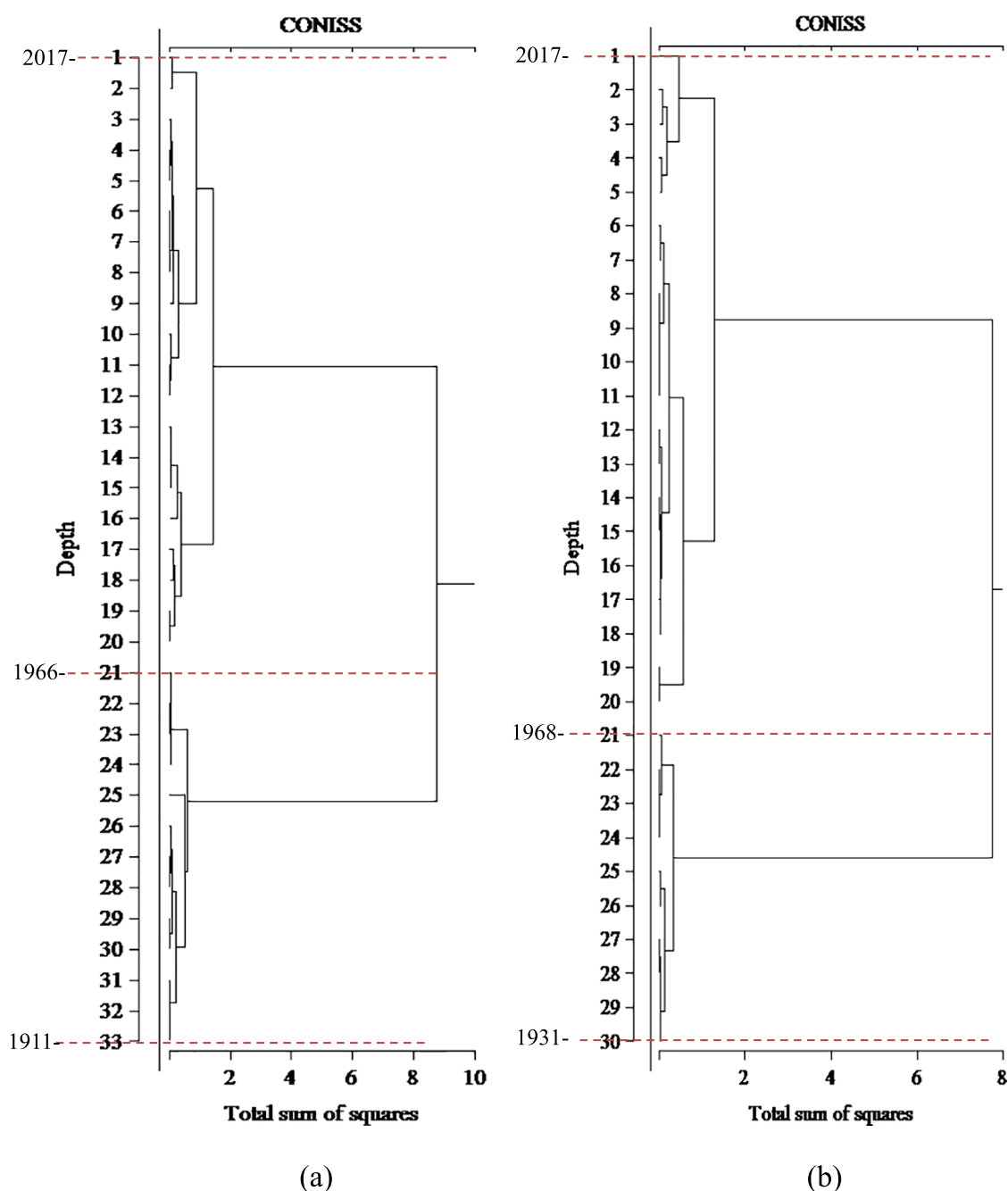


Fig. 4. Dendrogram derived from the CONISS cluster analysis of all detected pigments in C4 (a) and C14 (b) cores.

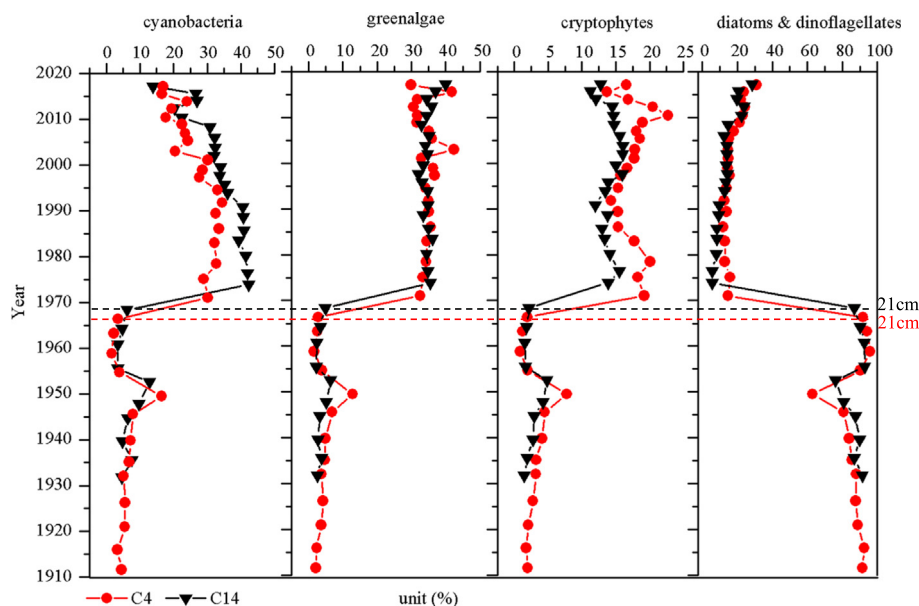


Fig. 5. Percent variation of the dominant phytoplankton groups at cores C4 and C14.

The large magnitude increases in  $\beta\beta$  Car and other pigment concentrations were observed during the 1960s at both stations (Fig. 2), indicating dramatic increases in phytoplankton biomass since the 1960s in Lake Chaohu.

### 3.2. Variations in the phytoplankton community structure

The phytoplankton pigments preserved in lake sediments here are derived from several major ecological groups (Roy et al., 2011). These include fossil pigments representative of diatoms and dinoflagellates (Diadino, Diato, Fuco, Peri, Hex-Fuco); green algae (Chl b, Lut, Pras); cyanobacteria (Cantha and Zea); cryptophytes (Allo); rhodophytes (Chl c2); and mesostigmatophytes (Neo) (Fig. 2). Using the various pigment profiles, percentages of the main group-specific pigments were calculated, which reflect the biomass changes of the predominant groups over time (Fig. 5). The results showed that the percentage of diatoms and dinoflagellates decreased from ~90% to ~15% since the 1960s. While cyanobacteria and green algae increased from ~5% to ~35%, ~40%, respectively after the 1960s. The percentage of cryptophytes increased from ~2% to ~15% since the 1960s (Fig. 5). Thus, the sediments below 21 cm represent diatoms and dinoflagellates dominance before the 1960s, and the overlying sediments represents dominance of cyanobacteria and green algae since the 1960s. The results of CONISS cluster analysis also shows that the historical period changes of algae biomass was found at 21 cm in cores from both stations (Fig. 4), reflecting significant increases of primary productivity at Lake Chaohu in the 1960s. These results are also supported by increasing concentrations of TOC, TN and TP, as well as ratios of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  since the 1960s (Zan et al., 2012). A recent investigation of the present-day phytoplankton community in Lake Chaohu identified 97 phytoplankton species, of which 35.1% were Cyanophyta, and 37.1% were Chlorophyta (Jiang et al., 2014). The results are generally consistent with those derived from sediment phytoplankton pigments in post-1960s period at Lake Chaohu (Fig. 5).

The potential drivers of algae succession at Lake Chaohu certainly include changes in hydrodynamic conditions, which changed significantly when the dam was constructed in 1963 (Chen et al., 2001; Waters et al., 2005; Zan et al., 2011). Decreasing discharge to/from the lake since dam construction accelerated the deposition of fine particles from the 1960s

onward (Zan et al., 2011). Strong positive correlations between fine grain sizes ( $d < 4 \mu\text{m}$  and  $4-8 \mu\text{m}$ ) and pigment concentrations (except for Hex-Fuco; Table 1) reflect the effect of stable depositional conditions on sediment pigment accumulation (Waters et al., 2005; Zan et al., 2011). Previous research has shown that changes in hydrodynamic conditions can induce large changes in the primary producer community, such as in Lake Apopka, Florida, which shifted from macrophyte- to phytoplankton-dominated in the late 1940s (Waters et al., 2005). The abundance and diversity of phytoplankton were stimulated by water movement at moderate velocities (Madsen et al., 2001).

Increasing levels of anthropogenically driven eutrophication has historically been considered to be the main driver of phytoplankton succession in most lakes (Smittenberg et al., 2005; Häder and Gao, 2014; Afrifa et al., 2016). The abundances of elemental C, N and P in sediments, all essential for phytoplankton growth, have been used widely to reconstruct trophic conditions and lacustrine palaeoproductivity (e.g., Zan et al., 2011; Paerl et al., 2016). The significant correlations between nutrients (and their proxies) (TOC, TN, TP,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ) and pigment concentrations (except for Hex-Fuco; Table 1;  $p < 0.01$ ) reflects the synchronicity of lacustrine trophic condition and algal biomass changes. Among all the nutrients proxies above,  $\delta^{13}\text{C}$  was correlated significantly but negatively with all the pigments (except for Hex-Fuco; Table 1;  $p < 0.01$ ), due to  $\delta^{13}\text{C}$  decreases as lacustrine primary productivity increases (Zan et al., 2012). Profile variation of phytoplankton pigments indicated increasing of primary productivity and succession of algae community at the 1960s in Lake Chaohu, which was consistent with the nutrient proxies (TOC, TN, TP,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ) record (Zan et al., 2011). Many studies have shown that lake phytoplankton communities are sensitive to environmental stressors, where changes in phytoplankton community structure and abundances were related to variation in lake trophic status (Häder and Gao, 2014; Afrifa et al., 2016), for instance, the demise of the green microalgae *Botryococcus braunii* due to early eutrophication in a Norwegian fjord (Smittenberg et al., 2005). Since the 1960s, increasing inputs of anthropogenic and bioavailable N and P from industrial, agricultural and domestic sewage sources to Lake Chaohu accelerated algae growth (Afrifa et al., 2016). The phytoplankton community shift in Lake Chaohu after the 1960s, from dominantly diatoms and dinoflagellates to dominantly cyanobacteria and green algae, was partly

driven by changes in hydrodynamic conditions and increasing anthropogenic nutrient concentrations (Zan et al., 2012).

In recent decades, the impact of climate change on lacustrine primary productivity and ecosystem succession has attracted considerable attention (Michalak, 2016; Hayes et al., 2016; Jambrina-Enríquez et al., 2017; O'Beirne et al., 2017). Meteorological conditions within the Lake Chaohu catchment changed measurably during the period of 1961–2017, including an increase in the annual average air temperature of 1.12 °C, and an increase in the annual average precipitation of 240.79 mm (Fig. 6). The Spearman correlations of annual average air temperature with Chl *a*, and  $\beta\beta$  Car in Lake Chaohu are 0.502, and 0.575, respectively ( $p < 0.01$ ; Table 2), which suggests that higher water temperatures promoted increases in primary productivity, which has been observed in other lakes which are not strongly nutrient-limited, or when increasing water temperatures do not produce stronger lake thermal stratification (Park et al., 2004; Warner and Lesht, 2015; O'Beirne et al., 2017). For example, water temperature and light intensity are known to affect cyanobacterial proliferation through regulation of the rates of carbohydrate production, gas vesicle synthesis, and cell photosynthesis (Zhen et al., 2016; Shi et al., 2017). The significant positive correlations between annual average air temperatures and specific phytoplankton pigments (Allo, Cantha, Chl *b*, Chl *c2*, Diadino, Diato, Fuco, Lut, Neo, Peri, Viola, Zea;  $p < 0.01$ ; Table 2) reflects the impact of increasing water temperatures on algae succession (Zhen et al., 2016; Michalak, 2016). Also, increased nutrient run-off caused by heavy rainfalls can play a crucial role in algae growth (Michalak, 2016; Toride et al., 2018). The significant positive correlation between annual average precipitation and Chl *a*, Chl *b*, Chl *c2*, Diadino, Diato, Fuco, and Viola concentrations were observed at Lake Chaohu ( $p < 0.01$ ; Table 2). Precipitation intensity and magnitude drive the rate and ratios at which N and P are exported to lakes (Hayes et al., 2016). The amounts of N and P, and their ratios modulate nutrient

limitations of lacustrine phytoplankton (Hayes et al., 2016; Jambrina-Enríquez et al., 2017), which plays a key role in determining community structure (Häder and Gao, 2014; Afrifa et al., 2016; Paerl et al., 2016; Michalak, 2016). Increased water temperatures and nutrient input via run-off can promote increased algae biomass, and the succession of cyanobacteria and green algae as the dominant phytoplankton groups in Lake Chaohu.

### 3.3. GAMs: contributions of human activities and climate change to algal community succession

GAMs analysis was applied to reveal when and how much the driving forces (human activities and climate change) contributed to the observed phytoplankton succession. The predictor variables were annual average air temperature and TP concentration (DI-TP), while the responses variables were the specific pigment concentrations of cyanobacteria, green algae, diatoms and dinoflagellates, cryptophytes, and total algae ( $\beta$  Carotene) for five GAMs, respectively (Fig. 7). The GAM explained 50.03% of the variance in total algae, with average air temperature accounting for 7.29%, and the TP concentration accounting for 42.74% (Table 3). The most significant predictor variable for total algae was TP ( $F = 36.32$ ,  $p < 0.001$ ). TP concentrations have increased by  $\sim 50 \mu\text{g L}^{-1}$  from the early to mid-1970s in Lake Chaohu (Chen et al., 2011). The rapid increase in TP concentrations induced positive effects on primary productivity and phytoplankton biomass, while the lower TP concentrations prevalent in Lake Chaohu before the 1970s had negative effects on total algae (Fig. S2; Fig. 7a).

The GAMs explained 47.83%, 47.84% and 50.79% of the variance in cyanobacteria, green algae and cryptophytes, respectively, with average air temperature accounting for 7.56%, 7.07% and 9.78%, respectively, and TP accounting for 40.27%, 40.77% and 41.01%, respectively (Table 3). The contribution of TP and average air temperature to

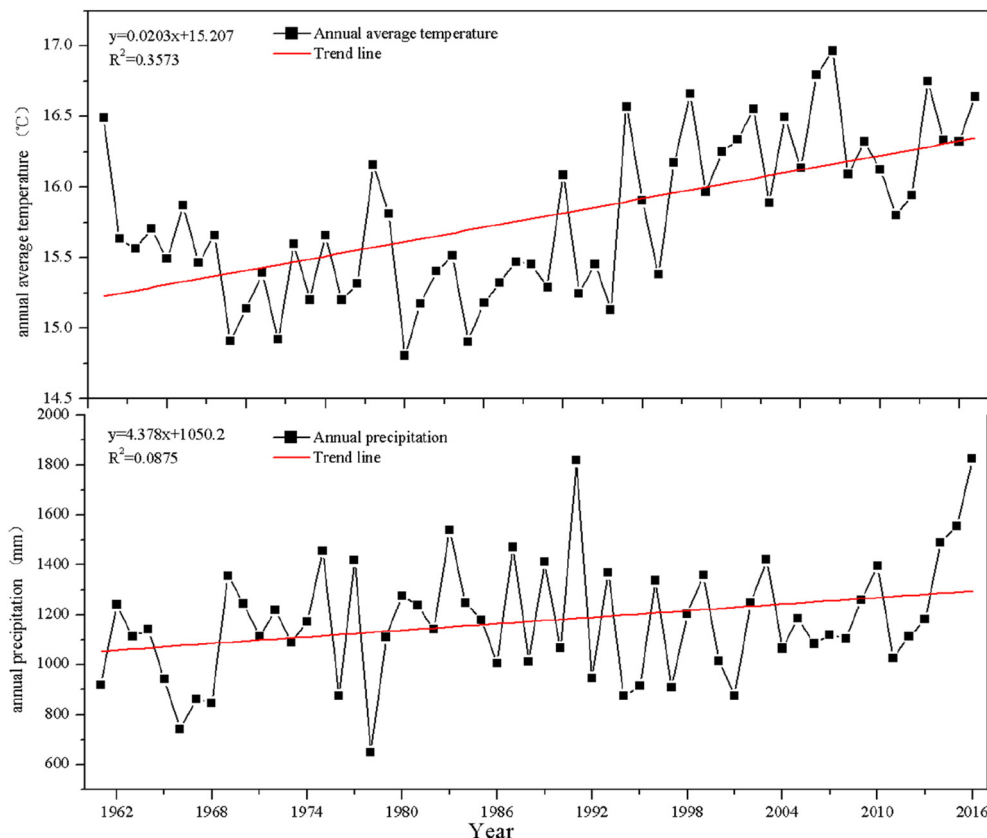


Fig. 6. Variation of annual average temperature and precipitation in the Lake Chaohu catchment from 1961 to 2016.

**Table 2**  
Spearman correlation coefficients between Hg and temperature, precipitation in cores C4 and C14 during 1961–2016.

	HexFuco	Allo	Cantha	Chla	Chlb	Chlc2	Diadino	Diatom	Fuco	Lut	MgDVP	Neo	Peri	Pheidea	Phea	Viola	Zea	$\beta$ Car
Tem	0.034	0.632**	0.603**	0.502**	0.500**	0.559**	0.590**	0.647**	0.531**	0.581**	0.306*	0.667**	0.660**	0.611**	0.596**	0.613**	0.383**	0.575**
Pre	−0.293*	0.245	0.225	0.435**	0.443**	0.420**	0.356**	0.303*	0.433**	0.216	0.258	0.249	0.256	0.305*	0.216	0.391**	0.166	0.181

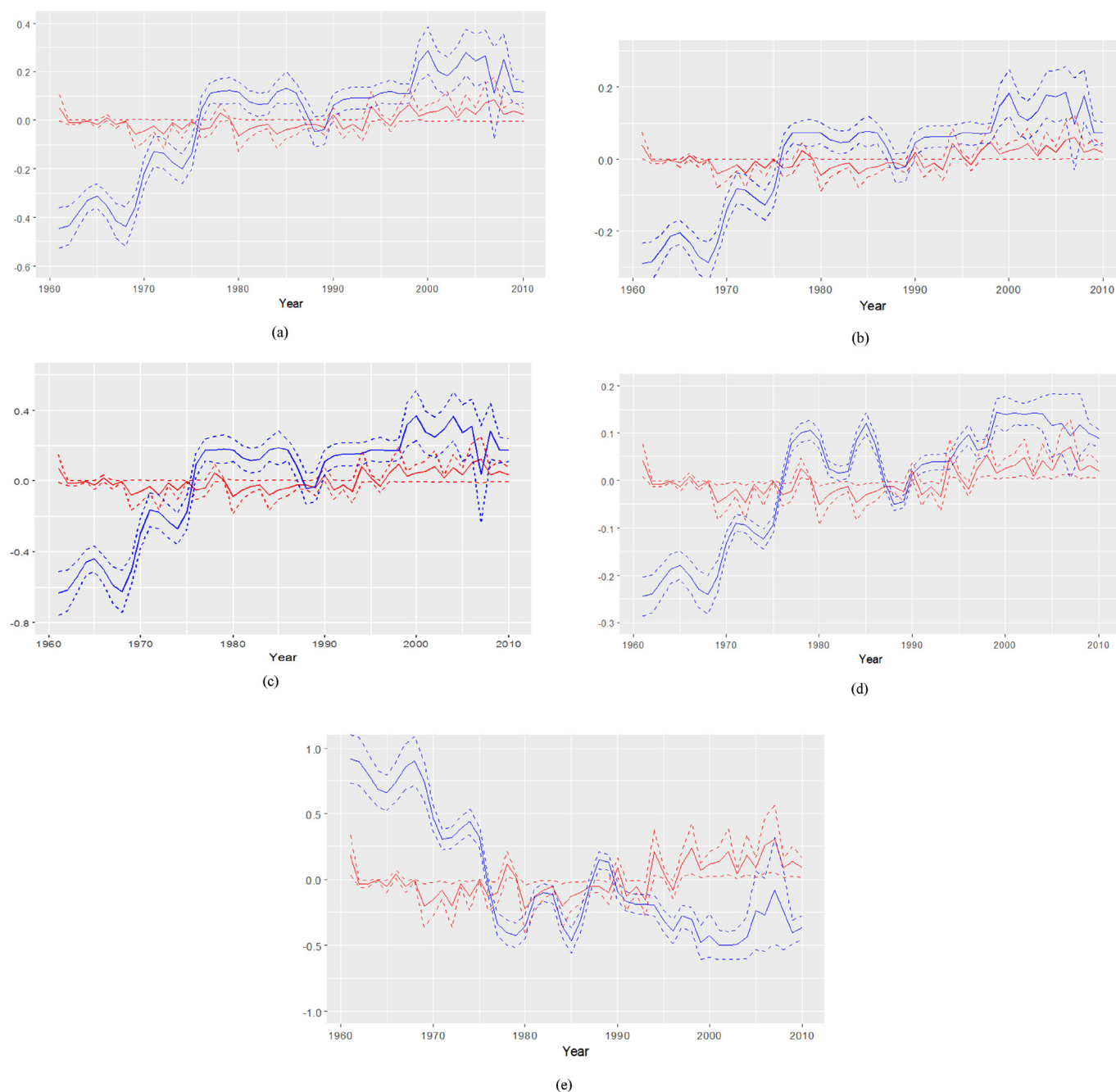
\*\* Correlations are significant at  $P < 0.01$  (two-tailed).\* Correlations are significant at  $P < 0.05$  (two-tailed).

cryptophytes was greater than that to cyanobacteria and green algae, because cryptophytes is more sensitive to water temperature and high organic water environment (Barone and Naselli-Flores, 2003). Increases in TP concentrations ( $F = 33.88$ ,  $p < 0.001$  for cyanobacteria;  $F = 34.17$ ,  $p < 0.001$  for green algae;  $F = 71.13$ ,  $p < 0.001$  for cryptophytes) were found to corresponded with increases in cyanobacteria, green algae and cryptophytes (Fig. 7b–d). TP is considered the more important variable in driving cyanobacterial dominance or bloom formation, as compared to warming average air temperatures, within a TP concentration range of 70 to 215  $\mu\text{g L}^{-1}$  (Wagner et al., 2009). TP concentrations in Lake Chaohu waters have consistently been higher than 70  $\mu\text{g L}^{-1}$  since the 1970s (Chen et al., 2011), indicating that TP has been the most influential factor affecting cyanobacterial growth. Responses of cyanobacteria, green algae and cryptophytes to increased average air temperatures were found to be positive since the mid-1990s (Fig. 7b, c). This is presumably because the optimum temperature for cyanobacteria photosynthesis and growth is higher than that for eukaryotic algae, which is a competitive advantage under warming conditions (Helbling et al., 2015; Havens and Paerl, 2015). Other research has shown that cyanobacterial blooms often occur in eutrophic lakes located at temperate latitudes during warm months, when a stable thermocline forms (Deshpande et al., 2014; Michalak, 2016; Shi et al., 2017). Warmer air and water temperatures act synergistically with nutrient loading to produce increased eutrophication and the dominance of cyanobacteria and green algae in Lake Chaohu.

The GAM explained 93.32% of the variance in diatoms and dinoflagellates, with average air temperature accounting for 20.74%, and TP concentration accounting for 72.58% (Table 3). TP concentration ( $F = 48.33$ ,  $p < 0.001$ ) was identified as the most significant influential factor on diatoms and dinoflagellates. A negative response of diatoms and dinoflagellates to TP concentrations was observed since the mid-1970s (Fig. 7e), as higher TP concentrations favored the proliferation of cyanobacteria, green algae and cryptophytes. The moderate average air temperature increases in the Lake Chaohu catchment induced positive effects on the abundances of total algae, diatoms and dinoflagellates, cyanobacteria, and green algae since the mid-1990s (Fig. 7). As air temperatures continue to increase, greater decreases in nutrient inputs to lakes are likely to be required to avoid major phytoplankton blooms (Wagner et al., 2009; Havens and Paerl, 2015; Michalak, 2016). The interactive effects of climate change and eutrophication on phytoplankton community structures is complex in Lake Chaohu (Shi et al., 2017), and their management is important for the control of harmful algal blooms (Havens and Paerl, 2015; Helbling et al., 2015).

#### 4. Conclusions

The concentration profiles of phytoplankton pigments in two sediment cores from Lake Chaohu provided valuable information on changes in phytoplankton community structure over decadal time scales. The pigment profiles and CONISS analysis define two distinct periods in terms of phytoplankton group dynamics: pre- and post-1960s. Since the 1960s, there has been a major increase in primary productivity, and a shift of the dominant phytoplankton community group from diatoms and dinoflagellates to cyanobacteria and green algae. The potential drivers of these changes include construction of the Chaohu Dam in 1963, increasing inputs of anthropogenic N and P, warmer average air temperatures, and increasing average annual precipitation. GAMs were used to quantify the relative contributions of human activities and climate change to phytoplankton succession. The results show that TP concentration contributions to the proliferation of total algae, cyanobacteria, green algae and cryptophytes were 42.27%, 40.27%, 40.77%, and 41.01%, respectively. These positive effects were observed since the mid-1970s, when TP concentrations increased considerably.



**Fig. 7.** GAMs analysis results for algae succession in Lake Chaohu. The figure presents the concentration of TP (blue line) and air temperature (red line) to the algae temporal changes including (a) total algae, (b) cyanobacteria, (c) green algae, (d) cryptophytes, and (e) diatoms and dinoflagellates. The graphs show when each predictor contributes significantly and how much each predictor contributes which is deduced from the values on y-axis scale.

Positive effects from increasing average air temperatures on total algae, cyanobacteria, green algae, cryptophytes, and diatoms and dinoflagellates were observed since the mid-1990s, indicating that an ever-

warming aquatic environment will have critical impacts on phytoplankton succession.

#### Acknowledgements

The National Key Research and Development Program of China (2017YFA0605003), and the National Natural Science Foundation of China (No. 91751114, 41521003) supported this study.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2018.08.081>.

**Table 3**  
GAMs analysis results for algae succession in Lake Chaohu.

	Tem (%)	TP (water) (%)
Cyanobacteria	7.561	40.27
Green algae	7.071	40.77
Diatoms & dinoflagellates	20.74	72.58
Cryptophytes	9.784	41.01
Total algae	7.291	42.74

## References

- Afrifa, Y.K., Callac, N., Fru, E.C., Wohlfarth, B., Wiech, A., Chabangborn, A., Smittenberg, R.H., 2016. A 150-year record of phytoplankton community succession controlled by hydroclimatic variability in a tropical lake. *Biogeosci. Discuss.* 13 (13), 3971–3980.
- Barone, R., Naselli-Flores, L., 2003. Distribution and seasonal dynamics of cryptomonads in sicilian water bodies. *Hydrobiologia* 502 (1–3), 325–329.
- Capo, E., Debroas, D., Arnaud, F., Perga, M.E., Chardon, C., Domaizon, I., 2017. Tracking a century of changes in microbial eukaryotic diversity in lakes driven by nutrient enrichment and climate warming. *Environ. Microbiol.* 168 (3), 335–351.
- Chen, Z., Li, J., Shen, H., Wang, Z., 2001. Yangtze River of China: historical analysis of discharge variability and sediment flux. *Geomorphology* 41 (2), 77–91.
- Chen, X., Yang, X., Dong, X., Liu, Q., 2011. Nutrient dynamics linked to hydrological condition and anthropogenic nutrient loading in Chaohu Lake (Southeast China). *Hydrobiologia* 661 (1), 223–234.
- Chen, Q., Nie, Y., Liu, X., Xu, L., Emslie, S.D., 2015. An 800-year ultraviolet radiation record inferred from sedimentary pigments in the Ross Sea area, East Antarctica. *Boreas* 44 (4), 693–705.
- Deshpande, B.N., Tremblay, R., Pienitz, R., Vincent, W.F., 2014. Sedimentary pigments as indicators of cyanobacterial dynamics in a hypereutrophic lake. *J. Paleolimnol.* 52 (3), 171–184.
- Häder, D.P., Gao, K., 2014. Interactions of anthropogenic stress factors on phytoplankton. *Front. Environ. Sci.* 3, 14.
- Havens, K.E., Paerl, H.W., 2015. Climate change at a crossroad for control of harmful algal blooms. *Environ. Sci. Technol.* 49 (21), 12,605–12,606.
- Hayes, N.M., Vanni, M.J., Horgan, M.J., Renwick, W.H., 2016. Climate and land use interactively affect lake phytoplankton nutrient limitation status. *Ecology* 96 (2), 392–402.
- Helbling, E.W., Banaszak, A.T., Villafañe, V.E., 2015. Global change feed-back inhibits cyanobacterial photosynthesis. *Sci. Rep.* 5, 14,514.
- Huo, S.L., Li, C.C., Xi, B.D., Yu, Z.Q., Yeager, K.M., Wu, F.C., 2017. Historical record of polychlorinated biphenyls (PCBs) and special occurrence of PCB 209 in a shallow fresh-water lake from Eastern China. *Chemosphere* 184, 832–840.
- Jambrina-Enríquez, M., Recio, C., Vega, J.C., Valero-Garcés, B., 2017. Tracking climate change in oligotrophic mountain lakes: recent hydrology and productivity synergies in Lago de Sanabria (NW Iberian Peninsula). *Sci. Total Environ.* 590–591, 579–591.
- Jiang, Y.J., He, W., Liu, W.X., Qin, N., Ouyang, H.L., Wang, Q.M., et al., 2014. The seasonal and spatial variations of phytoplankton community and their correlation with environmental factors in a large eutrophic Chinese lake (Lake Chaohu). *Ecol. Indic.* 40 (5), 58–67.
- Jiang, T., Yu, Z., Qi, Z., Chai, C., Qu, K., 2017. Effects of intensive mariculture on the sediment environment as revealed by phytoplankton pigments in a semi-enclosed bay, South China Sea. *Aquac. Res.* 48 (4).
- Li, C.C., Huo, S.L., Xi, B.D., Yu, Z.Q., Zeng, X.Y., Zhang, J.T., et al., 2015. Historical deposition behaviors of organochlorine pesticides (OCPs) in the sediments of a shallow eutrophic lake in eastern China: roles of the sources and sedimentological conditions. *Ecol. Indic.* 53 (02), 1–10.
- Madsen, J.D., Chambers, P.A., James, W.F., Koch, E.W., Westlake, D.F., 2001. The interaction between water movement, sediment dynamics and submersed macrophytes. *Hydrobiologia* 444 (1–3), 71–84.
- Michalak, A.M., 2016. Study role of climate change in extreme threats to water quality. *Nature* 535 (7612), 349–350.
- Mwangi, H.M., Julich, S., Patil, S.D., McDonald, M.A., Feger, K.H., 2016. Relative contribution of land use change and climate variability on discharge of upper Mara River, Kenya. *J. Hydrol. Reg. Stud.* 5 (1), 244–260.
- O’Beirne, M.D., Werne, J.P., Hecky, R.E., Johnson, T.C., Katsev, S., Reavie, E.D., 2017. Anthropogenic climate change has altered primary productivity in Lake Superior. *Nat. Commun.* 8, 15713.
- Paerl, H.W., Scott, J.T., McCarthy, M.J., Newell, S.E., Gardner, W.S., Havens, K.E., et al., 2016. It takes two to tango: when and where dual nutrient (N & P) reductions are needed to protect lakes and downstream ecosystems. *Environ. Sci. Technol.* 50 (20), 10805–10813.
- Park, S., Brett, M.T., Muller-Solger, A., Goldman, C.R., 2004. Climatic forcing and primary productivity in a subalpine lake: interannual variability as a natural experiment. *Limnol. Oceanogr.* 49 (2), 614–619.
- Pearce, J.L., Beringer, J., Nicholls, N., Hyndman, R.J., Tapper, N.J., 2011. Quantifying the influence of local meteorology on air quality using generalized additive models. *Atmos. Environ.* 45 (6), 1328–1336.
- Qi, Y.J., Hu, S.B., Huo, S.L., Xi, B.D., Zhang, J.T., Wang, X.W., 2015. Spatial distribution and historical deposition behaviors of perfluoroalkyl substances (PFASs) in sediments of Lake Chaohu, a shallow eutrophic lake in Eastern China. *Ecol. Indic.* 57, 1–10.
- Reuss, N., Conley, D.J., Bianchi, T.S., 2005. Preservation conditions and the use of sediment pigments as a tool for recent ecological reconstruction in four northern European estuaries. *Mar. Chem.* 95 (3–4), 283–302.
- Romero-Viana, L., Keely, B.J., Camacho, A., Vicente, E., Miracé, M.R., 2010. Primary production in Lake la Cruz (Spain) over the last four centuries: reconstruction based on sedimentary signal of photosynthetic pigments. *J. Paleolimnol.* 43 (4), 771–786.
- Roy, S., Llewellyn, C., Egeland, E.S., Johnsen, G., 2011. Phytoplankton pigments. [www.cambridge.org/9781107000667](http://www.cambridge.org/9781107000667).
- Scheffer, M., 2004. *Ecology of Shallow Lakes*. Springer Netherlands.
- Shi, K., Zhang, Y., Zhou, Y., Liu, X., Zhu, G., Qin, B., et al., 2017. Long-term Modis observations of cyanobacterial dynamics in Lake Taihu: responses to nutrient enrichment and meteorological factors. *Sci. Rep.* 7, 40326.
- Smittenberg, R.H., Baas, M., Schouten, S., Sinninghe Damsté, J.S., 2005. The demise of the alga *Botryococcus braunii* from a Norwegian fjord was due to early eutrophication. *The Holocene* 15 (1), 133–140.
- Szymczak-Żyła, M., Kowalewska, G., Louda, J.W., 2011. Chlorophyll-a, and derivatives in recent sediments as indicators of productivity and depositional conditions. *Mar. Chem.* 125 (1), 39–48.
- Szymczak-Żyła, M., Krajewska, M., Winogrodow, A., Zaborska, A., Breedveld, G.D., Kowalewska, G., 2016. Tracking trends in eutrophication based on pigments in recent coastal sediments. *Oceanologia* 59 (1), 1–17.
- Toride, K., Cawthorne, D.L., Ishida, K., Kavvas, M.L., Anderson, M.L., 2018. Long-term trend analysis on total and extreme precipitation over Shasta dam watershed. *Sci. Total Environ.* 626, 244–254.
- Wagner, C., Adrian, R., Williamson, C.E., Saros, J.E.G., Vincent, W.F., Smol, J.P., 2009. Cyanobacteria dominance: quantifying the effects of climate change. *Limnol. Oceanogr.* 54 (6-part 2), 2460–2468.
- Warner, D.M., Lesht, B.M., 2015. Relative importance of phosphorus, invasive mussels and climate for patterns in chlorophyll a and primary production in Lakes Michigan and Huron. *Freshw. Biol.* 60 (5), 1,029–1,043.
- Waters, M.N., Schelske, C.L., Kenney, W.F., Chapman, A.D., 2005. The use of sedimentary algal pigments to infer historic algal communities in Lake Apopka, Florida. *J. Paleolimnol.* 33 (1), 53–71.
- Wood, S., 2015. Package “mgcv.”. <http://CRAN.R-project.org/package=mgcv>.
- Xu, Y., Gao, X.J., Shen, Y., Xu, C.H., Shi, Y., Giorgi, F., 2009. A daily temperature dataset over China and its application in validating a RCM simulation. *Adv. Atmos. Sci.* 26 (4), 763–772.
- Zan, F.Y., Huo, S.L., Xi, B.D., Su, J., Li, X., Zhang, J.T., Yeager, K., M., 2011. A 100 year sedimentary record of heavy metal pollution in a shallow eutrophic lake, Lake Chaohu, China. *J. Environ. Monit.* 13 (10), 2,788–2,797.
- Zan, F.Y., Huo, S.L., Xi, B.D., Zhu, C.W., Liao, H.Q., Zhang, J.T., et al., 2012. A 100-year sedimentary record of natural and anthropogenic impacts on a shallow eutrophic lake, Lake Chaohu, China. *J. Environ. Monit.* 14 (3), 804–816.
- Zapata, M., 2000. Separation of chlorophylls and carotenoids from marine phytoplankton: a new HPLC method using a reversed phase C8 column and pyridine-containing mobile phases. *Mar. Ecol. Prog. Ser.* 195 (3), 29–45.
- Zastepa, A., Taranu, Z.E., Kimpe, L.E., Blais, J.M., Gregoryeaves, I., Zurawell, R.W., Pick, F.R., 2017. Reconstructing a long-term record of microcystins from the analysis of lake sediments. *Sci. Total Environ.* 579, 893–901.
- Zhang, M., Xie, C.X., Hansson, L.A., Hu, W.H., Che, J.P., 2012. Trophic level changes of fishery catches in Lake Chaohu, Anhui Province, China: trends and causes. *Fish. Res.* 131, 15–20.
- Zhang, X.K., Liu, X.Q., Wang, H.Z., 2014. Developing water level regulation strategies for macrophytes restoration of a large river-disconnected lake, China. *Ecol. Eng.* 68, 25–31.
- Zhen, Y., Min, Z., Shi, X., Kong, F., Ma, R., Yang, Y., 2016. Nutrient reduction magnifies the impact of extreme weather on cyanobacterial bloom formation in large shallow Lake Taihu (China). *Water Res.* 103, 302–310.